

CALCULATION AND DESIGN OF A RF CAVITY FOR A NOVEL COMPACT SUPERCONDUCTING CYCLOTRON FOR RADIOISOTOPE PRODUCTION (AMIT)*

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Abstract

The AMIT (Advanced Molecular Imaging Techniques) cyclotron will be a 8.5 MeV, 10 μ A, CW, H^+ accelerator for the purpose of radioisotope production. It includes a superconducting, weak focusing, 4 T magnet, which allows for a small extraction radius and a compact design. The RF cavity design has to deal with challenging requirements: high electric fields created by the required accelerating voltage (60 kV), a narrow aperture of the magnet leading to high capacitances and thermal losses, and a requirement for a small overall size of the cavity. A quarter wave resonator with one dee (two acceleration gaps) design was chosen. Calculations with numerical codes such as HFSS and ANSYS have been performed to compute the main RF parameters and the stresses and deformations of the cavity due to the power losses and vacuum operation. Finally, the fluid dynamics of the cooling circuits have been carefully studied.

INTRODUCTION

Positron-emission tomography (PET) is a broadly used technique around the world for biomedical human imaging. Therefore, there is a high and increasing demand for positron emitter isotopes. The most effective PET isotopes (like ^{11}C or ^{18}F) have a short half-life (20 min and 2 h, respectively). Low energy cyclotrons (below 15 MeV) are the most widely used devices for their production. There is a growing interest in developing compact, light and cheap cyclotrons, capable of running at a small facility and producing the isotopes close to the patient, reducing the transport inconveniences and the loss of activity of the isotopes.

Spanish AMIT collaboration aims at producing a compact cyclotron for production of ^{11}C and ^{18}F isotopes. It will accelerate 10 μ A of H^+ ions to 8.5 MeV. It includes a superconducting, weak focusing, 4 T magnet.

CONCEPTUAL DESIGN

Table 1 summarizes the technical specifications of the cavity. Since AMIT cyclotron is of classical type, the magnet air gap has uniform height. Its RF cavity configuration is based on the typical 180 degree dee, at the end of a quarter wave coaxial resonator. The weak focusing limits the number of particle turns before the beam is lost. This imposes, for the required final energy, a

minimum of 60 kV per gap, according beam dynamics simulations [1].

Other configurations have been studied trying to reduce RF power losses. That dissipation is due to the currents necessary to charge the capacitance between the dee and the vacuum chamber wall. A 90 degree dee features half the capacitance, that is, half of the charging currents, one quarter of the initial power losses. However, the nominal frequency should be doubled, which would yield the same original power losses for the same gap voltage. Furthermore, the phase shift is doubled, so the gap voltage should be increased to reach the same output beam energy according with beam dynamics simulations, resulting in additional RF power losses.

Two 90 degree dees do not allow decreasing the gap voltage and consequently the power losses, because the phase shift is doubled with the frequency, arising similar problems than the single 90 degree dee configuration. Furthermore, this layout is hardly compatible with the space necessary for the instrumentation and beam extraction [2].

Table 1: Cavity Technical Specifications

Frequency	60 MHz
Gap voltage	60 kV
Magnet air gap	74 x 280 mm
Maximum beam extraction radius	115 mm
Maximum beam axial excursion	± 6 mm
Tuning range	± 140 kHz

The aim is to keep the peak electric field below 1.5 times Kilpatrick criterion, that is, below 14.2 MV/m, at all the parts except the puller. The peak temperature shall be below 60°C to keep moderate thermal emission of electrons and increase of copper resistivity due to heating.

ELECTROMAGNETIC CALCULATIONS

Ansys (including the high frequency electromagnetic package HFSS), has been used to perform the RF simulations [3]. Firstly, a static electric model was used to optimize the central region geometry. Eigenmode HFSS analysis was performed afterwards to achieve the resonance and to get the field maps. Finally, both input power coupler and pickup probe were designed using the HFSS DrivenModal analysis.

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Central Region Optimization

The central region is the domain in which the particle makes the initial turns, which have a small radius due to the high magnetic field. The electric field map is defined by the geometries and positions of the ion source, the puller and the gap between the dee and the dummy dee. It has a complex 3D distribution, without symmetries. The beam properties have a large sensitivity to this region field map, as responsible for the initial longitudinal and transversal focusing.

The central region dimensions are very small compared to the wave length. Therefore, electric field can be calculated using an electrostatic model in which the ion source and the cavity walls are kept at null voltage, while the dee and puller are at 60 kV. This simple model allows the accurate definition of the geometry details, while keeping a moderate computing burden.

An iterative process leads to an optimized geometry of the puller and ion source geometries, which produce a proper electric field map from the point of view of beam dynamics and, at the same time, keeps the peak electric field as low as possible (24 MV/m, Fig. 1). Meanwhile, the peak electric field at the dees is 13 MV/m, within specifications.

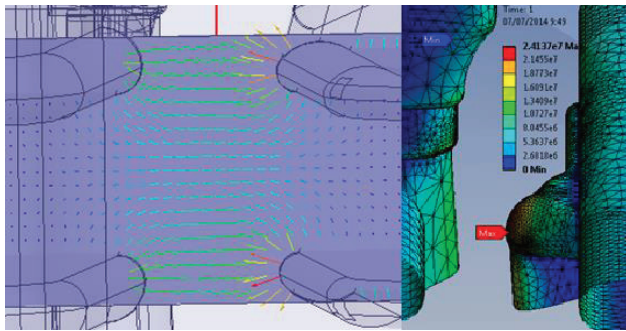


Figure 1: Electric field map in cyclotron central region.

Eigenmode Analysis

The cavity geometry was optimized to get the nominal resonant frequency with minimum power losses, that is, maximum shunt impedance. The power loss density is proportional to the square of the magnetic field. In a coaxial cable, the peak magnetic field takes place at the surface of the inner conductor and it decreases when the radius increases. Besides, a large radius of the inner conductor also increases mechanical stiffness, which is good because of the horizontal working position. Nevertheless, it cannot be too close to the outer conductor, since capacitive effects become significant.

On the other hand, power losses decrease for a short cavity, that is, a large inductance per unit length at the resonator. Inductance of a coaxial cable increases with the radius of the outer conductor, for a given inner conductor (if it is decreased, power loss density would be enhanced).

In consequence, a large hole is drilled in the iron yoke to enlarge the resonator as close the dee as possible (see Fig. 2). A symmetric hole is also drilled to keep the symmetry of the magnetic field. This decreases by 26%

the surface loss density in that area of the liner, which happens to be very difficult for cooling, from a maximum of 5 W/cm² to 3.7 W/cm². The total power dissipation is also reduced by 21%, from 6.8 to 5.36 kW (Fig. 3).

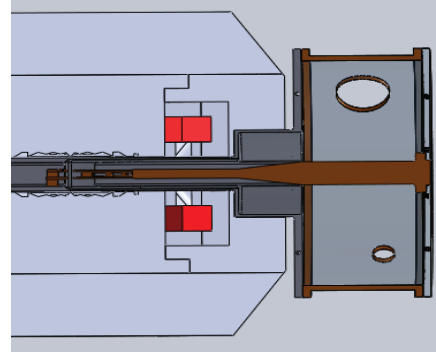


Figure 2: Cavity cross section showing the enlargement of the outer conductor to decrease power losses.

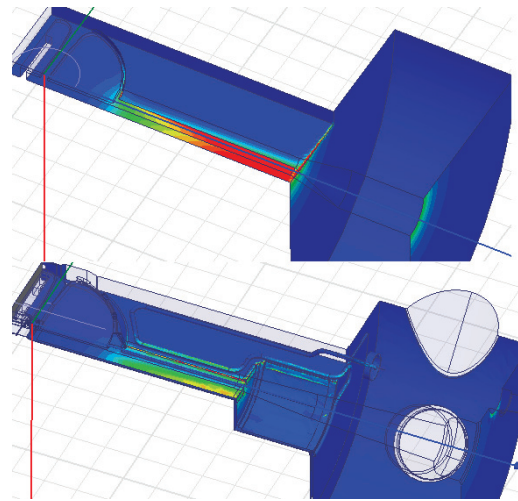


Figure 3: Surface heat generation on liner without (up) and with (down) iron hole.

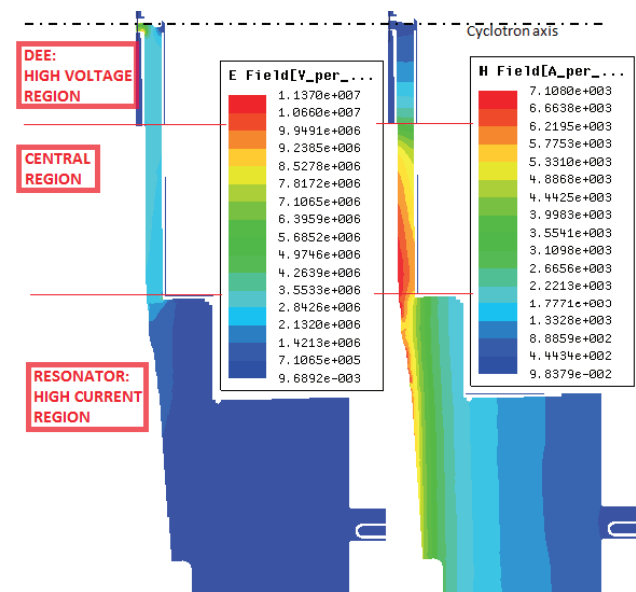


Figure 4: Electric and magnetic field distribution in the cross section. Cyclotron axis is horizontal.

The calculated unloaded quality factor Q_0 is 5250, the shunt impedance is 353.8 k Ω and the power dissipation, 5.36 kW. Electric fields are lower than those in the central region, as expected (Fig. 4). The high magnetic field area has, accordingly, the highest heat dissipation and is, therefore, the most challenging point regarding cooling.

Two plungers placed at the resonator are foreseen to keep the resonant frequency under temperature or dimension variations. Both will be used by the control system in closed-loop.

DrivenModal Analysis

This analysis evaluates the frequency response of the cavity by the calculation of the S-parameters and allows for optimizing the design of input power coupler and pickup probe.

Power coupler will be of inductive type placed at the resonator. It will be equipped with a rotatable assembly to allow for the final adjustment of the coupling factor, the target of which is fixed at 1, as an optimum regarding efficiency for such a low beam loading.

The pickup probe is also of inductive type, located inside a resonator port. Its position and size is chosen to get a reasonable transmission coefficient ($S_{21} = -60$ dB in this case), in order to provide a proper power level to the control system.

MECHANICAL ANALYSIS

Structural Calculations

Due to the space restrictions and the low magnetic permeability requirement, the best material choice to manufacture the cavity walls is stainless steel. The thickness is reduced at the regions with high capacitance to decrease it as much as possible and, consequently, power losses. Mechanical stresses due to vacuum operation are kept within reasonable limits, with a safety factor above 2 (see Fig. 5). Non-negligible deformations (up to 0.3 mm) were detected at the weakest locations. Some of them will be compensated in the detailed design with the fabrication tolerances.

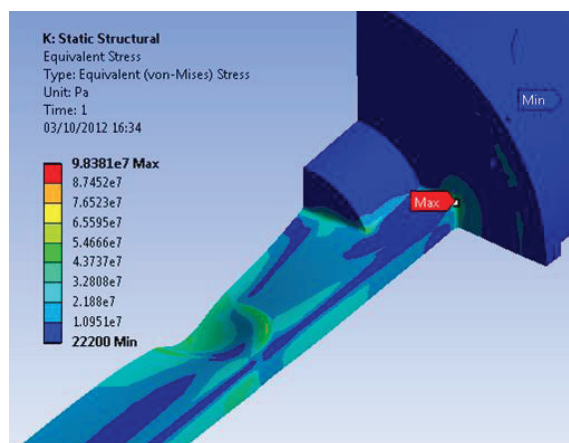


Figure 5: Von-Mises equivalent stress at the cavity walls.

Thermal Calculations

The surface heat deposition calculated with the electromagnetic model has been imported as a heat load distribution into the thermal model. Water at 18°C was used as coolant. When using a copper coating on the steel walls, cooling was cumbersome due to the low thermal conductivity of the stainless steel. Therefore, it was decided to include a copper liner with dedicated cooling at the regions with high power loss density, to get profit of the good thermal conductivity of the copper. Besides, it is much more resistant to multipacting impacts.

The stem is internally cooled, but the dees are cooled just by conduction. This approach eases the fabrication and allows for thinner dee walls, that is, the distance from the dee to the vacuum chamber increases, the capacitance decreases and, accordingly, the overall power losses. This parameter has a strong influence on the power losses: when it is increased from 16 to 20 mm, the power losses are reduced by 20%.

Figure 6 shows the temperature distribution. The maximum temperature at the dees is 51°C, while 60.5°C are reached at the bottom endplate, but there the electric field is very low, so expected multipacting effects are not dangerous.

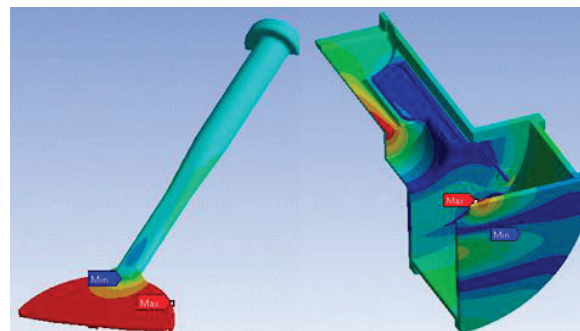


Figure 6: Temperature distribution at stem and dee (left) and cavity walls (right).

CONCLUSION

The RF cavity for the AMIT cyclotron shows a number of important design challenges, mainly coming from the machine compactness. Its design is the result of a complex and iterative process involving electromagnetic and mechanical simulations. The result of this process has been presented. The objectives regarding external dimensions, effective accelerating voltage and field map, power loss and temperatures were achieved.

REFERENCES

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